Hydrogen Economy and Sustainability: Towards a PtX Roadmap for Uruguay

ISC_3 White Paper

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Contents

Foreword

Our aim with this paper is to reach multiple reader groups. As a service to our readers, we have made sure that you can read only those passages in which you are interested: To obtain a quick overview, please spend two minutes on our "Executive Summary" on page 5 and recommendations "It is smart..." on page 34. However, if you want to follow the entire process and learn whether ISC_3 can offer you a similar service, you can immerse yourself in the blue chapters on pages 6 – 11 as well. To obtain a good insight into the technical aspects, just ignore the introductory chapters and jump immediately to page 13. We are sure that in this way we can offer you both efficient and interesting reading! The editors:

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About ISC_3

ISC_3 is the international centre that promotes the **transition of the chemicals industry and related sectors to Sustainable Chemistry**. The centre takes a multi-stakeholder approach, targeting policymakers, the public and private sectors, academia and civil society. ISC_3 contributes to international chemicals policy, develops professional and academic training measures, offers advisory services, fosters innovation, supports entrepreneurship and conducts research. Its international activities take place in selected developing and emerging countries worldwide. ISC_3 is hosted by the German GIZ (Gesellschaft für Internationale Zusammenarbeit) in cooperation with Leuphana University Lüneburg as ISC_3 Research & Education Hub and DECHEMA e. V. (Society for Chemical Engineering and Biotechnology) as ISC_3 Innovation Hub. The centre was founded in 2017 on the initiative of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and the German Environment Agency (UBA).

Executive Summary

Harmful developments and consequences when introducing a whole new energy system along with new technologies are foreseeable!

This was a claim made by ISC_3 within a consulting project with two workshops and participants from Uruguay aimed at **navigating towards a sustainable hydrogen roadmap**. The workshop focused on Power-to-X (PtX), which embraces gaseous, fluid or solid energy carriers. Many issues concerning negative side effects and how to avoid them were raised that can help to achieve a more sustainable development. The aspiration is that all those who are preparing or **planning a similar energy transition process will benefit from these reflections**.

First, this paper provides a case study overview of the situation in Uruguay. During the first stage of its energy transition, this small Latin-American country achieved a high percentage of renewable energy and is now seeking to de-fossilise various sectors during the **second stage of the transition towards green hydrogen,** developing actions that include, among others, the ongoing call for the construction of the first pilot project.

In the Introduction, general thoughts on the potential offered by the hydrogen economy help to delve into the topic of PtX. **Hydrogen and its downstream products** can be utilised as **storage media and as building blocks** for the chemical and related industries. It is essential that the efforts towards **energy security in importing countries consider the interests of exporting countries.** These considerations go hand in hand with further questions that focus on **Sustainable Chemistry.**

The main part is divided, like the PtX process, into three steps**: input, process and output.** The Input Phase focuses on how and where to obtain the necessary energy, carbon source and water supply. It also discusses the **environmental and social side effects** of large infrastructure projects that are necessary to obtain the indispensable inputs. Additional and surplus renewable energies and the preferred use of existing infrastructure are important parts of such a sustainable development. The Process Phase looks at possibilities to **reduce the use of precious metals** (but also further construction materials), good **water management**, scaling options and integrating PtX plants in existing chemical parks. The Output Phase deals with the challenges of the **storage and transport** of hydrogen and other PtX products, such as ammonia, PtLiquid (e.g. methanol) and PtGas (e.g. methane). Cost aspects are also considered.

In the section "It is smart…", common denominators based on economic, environmental, social or governance **(EESG) factors** are identified: For example, developing the demand side, creating jobs, protecting the environment, preserving resources, respecting social aspects, and regulations and incentives need to be part of an overarching strategy in order to develop a **future-proof PtX-based hydrogen economy** in the country.

Finally, the Outlook section discusses whether these findings are transferable to other regions of the world. Here, Morocco serves as a **case study** – with completely different prerequisites regarding its geography, availability of regional regenerative energy, off-taker structure as well as social and political environment.

Sustainable Chemistry

The mission of ISC_3 is to facilitate the transformation towards Sustainable Chemistry as a major contribution to achieving the UN Sustainable Development Goals. ISC_3 references the **10 key characteristics**[1] of Sustainable Chemistry, see table 1.

To avoid unwanted consequences on an economic, environmental, social or governance (EESG) level, the current and future practice of the chemical and allied industries need to be aligned with general **key sustainability characteristics,** such as sufficiency, consistency, efficiency and resilience. This, together with respecting the planetary boundaries as well as precaution as core principles, will create new economic opportunities that will simultaneously go beyond purely economic-driven decisions. They will generally lead to benefits for the planet as a whole and all societies throughout the world because they also address the Sustainable Development Goals (SDGs) of the United Nations. The 10 key characteristics must be applied to all steps in the chemical production value chain – from resources to manufacturing, to application, considering the end of life of products and recycling as well as services by all stakeholders. The transformation of current education models as well as reskilling and upskilling the workforce also need to be addressed in order to progress towards Sustainable Chemistry. Sustainable Chemistry is a framework that provides guidance on how chemistry, as a scientific and economic asset spanning multiple supply chains and consequently the whole life cycle, can comply with the principles of sustainability for the betterment of our planet. These key characteristics also have to be exhibited by PtX projects that are neither "green" nor sustainable per se. Thinking about the impact of a technology before it is introduced would seem expedient. Integrated, holistic and forward-oriented thinking is essential in today's world.

Holistic Approach	Precautionary Principle	Systems Thinking	Ethical & Social Responsibility	Circularity
Collaboration & Transparency	Sustainable & Responsible Innovation	Sound Chemicals Management	Green Chemistry	Life Cycle

TABLE 1:
10 key characteristics of Sustainable Chemistry

Source: ISC_3 (2021)

1 ISC_3 (2021) https://www.isc3.org/fileadmin/user_upload/Documentations_Report_PDFs/ISC3_Sustainable_Chemistry_key_characteristics_20210113.pdf

General **Background**

Access to affordable energy and chemical base materials is vital to flourishing economies. The world is currently recognising the importance of this fragile system, particularly against the background of the Russian war against Ukraine. However, besides the political and human dimensions, this crisis is a further one related to energy: Climate change, pollution, depleting sources and political conflicts are accompanied by massive environmental, social and economic issues.

ISC_3 compiles studies on **current global challenges** using stakeholder dialogue as the main approach. The aim is to look at regional aspects and issues together with cross-sectorial and cross-organisational experts. The meta level of the current study is a nexus between chemistry and energy and can be introduced by the question: How can Sustainable Chemistry contribute to sustainable energy systems and vice versa, and how exactly? The spotlight of this paper is on the hydrogen economy, more specifically Power-to-X technologies and their potential side effects. It addresses the case study of Uruguay, a lighthouse country for the LATAM region since it has passed the first transition to renewable energy sources (98% electricity from renewables in 2020[2]) and is currently preparing a hydrogen roadmap. The goal of ISC_3 is to include Sustainable Chemistry thinking in roadmaps and project concepts from the very outset in order to achieve better starting conditions for fulfilling sustainability goals.

This white paper was developed against the background of a two-day PtX training session, expert presentations, groupwork and analyses. It presents an outcome of the whole process – a **stakeholder dialogue** with local and international experts from Chile, Ecuador, Germany, Morocco and Uruguay on the one hand and experts from ISC_3 and GIZ on the other. In 2020, ISC_3 organised workshops together with the National Agency for Research and Innovation of Uruguay (ANII). In 2021, cooperation between ISC_3, PtX-Hub Berlin (GIZ) and the Ministry of Industry, Energy and Mining (MIEM) of Uruguay was established. A **Green Hydrogen and Power-to-X training programme** was developed for 40 MIEM participants by PtX-Hub and organised by ISC_3 in October 2021. The workshop Side Effects of Power-to-X and a Hydrogen Economy followed, with about 50 experts from different countries. After the release of the Uruguayan green hydrogen roadmap, 40 participants of the training programme met again for a transfer workshop to discuss the national strategy and roadmap for PtX in Uruguay as well as to develop further strategies based on a SWOT analysis moderated by ISC_3.

2 IRENA (2019) https://www.irena.org/-/media/Files/IRENA/Agency/Events/2019/Jul/2019-07-17-Workshop-Minutes-Uruguay.pdf?la=en&hash=B5CE4AF4958D3424241E6B37B111B3C833B53AD1

Situation in **Uruguay**

Uruguay can boast a very **high percentage of renewable energies** in the electricity sector (approx. 98%), mainly hydropower and wind (see figure 1 and table 2)[3].

Thanks to the massive use of renewable energy sources over the last 12 years, Uruguay has managed to reverse its position in the region, moving from an energy sink to a net exporter since 2013.

In 2021, significantly more electricity was exported (2820 GWh) than imported (55 GWh)[4], as is shown in figure 1. In 2021, already 20% of total power was exported to neighbouring countries. Wind resource surveys in Uruguay show a very good level overall, with greater availability of winds in the eastern zone. Photovoltaics (PV) only contributes 3% at present, but there is considerable potential thanks to high irradiation

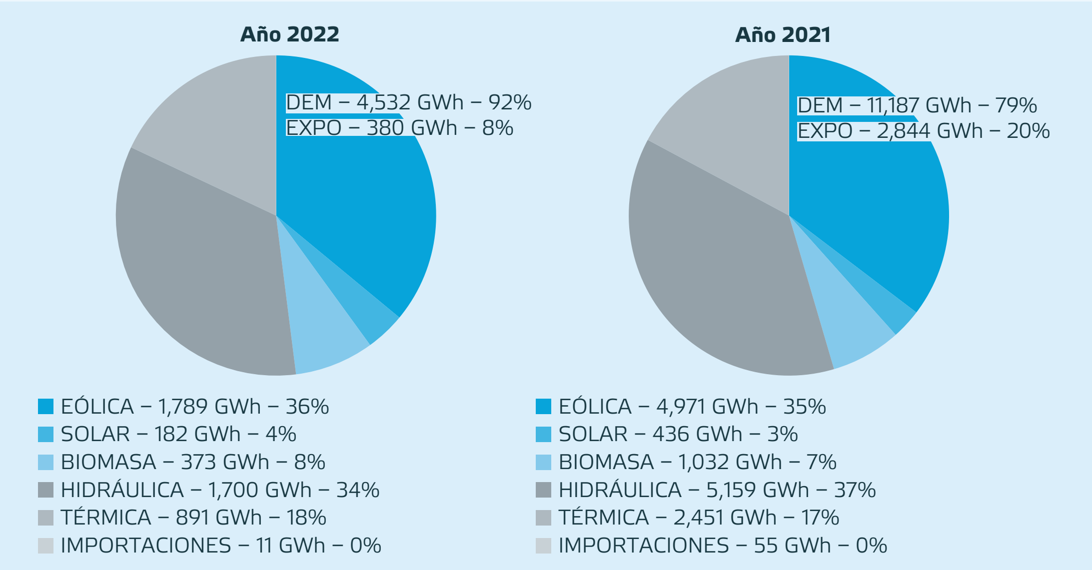


FIGURE 1:
Export and import of electricity in Uruguay

Source: ADME (2022)

3 IRENA (2019) https://www.irena.org/-/media/Files/IRENA/Agency/Events/2019/Jul/2019-07-17-Workshop-Minutes-Uruguay.pdf?la=en&hash=B5CE4AF4958D3424241E6B37B111B3C833B53AD1 retrieved on 15.04.2022 16:20

4 ADME (2022) https://www.adme.com.uy/controlpanel.php retrieved on 15.04.2022 16:25

rates and many sunshine hours per year[5]. Uruguay has managed to generate more electricity from renewable energies than it consumes on the domestic market and even sell some of the surplus electricity to neighbouring countries; this strategy of mainly relying on renewable energy sources to generate power is referred to as the

1st stage of the energy transition.

All renewable energy marketed in Uruguay can be certified according to the System of Renewable Energy Certificates (SCER)[6, 7].

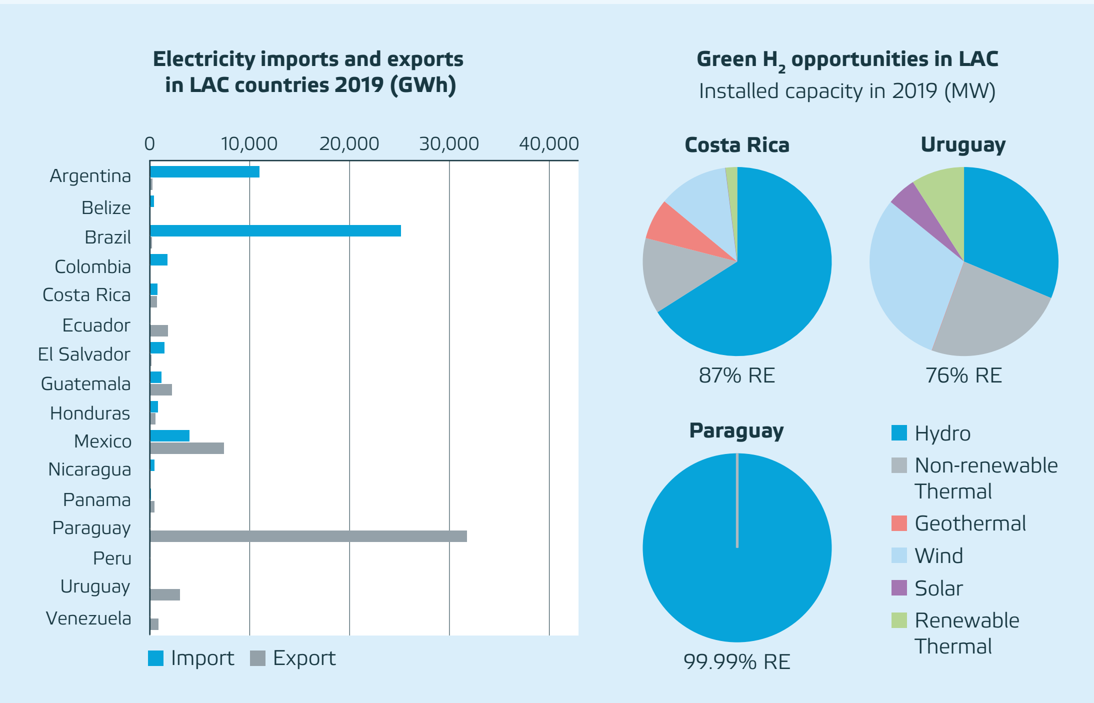


FIGURE 2:
Green H_2 opportunities in Latin American countries

Source: Blanco (2021), see also ADME (2022), Own diagram with SieLAC database

5 https://solargis.com/maps-and-gis-data/download/uruguay retrieved on 15.04.2022 16:30

6 SCER is the Spanish acronym.

7 See system description at https://certificacion-energiarenovable.miem.gub.uy/ retrieved on 15.04.2022 16:35

Today, with 20 to 40 USD/MWh, the costs for electricity generation by PV and onshore wind parks are competitive[8]. Uruguay already meets many conditions that attract investors: Among others, there is sufficient land, a stable and democratically governed society, a functioning education system and established relations in the region and beyond. After the successful implementation of the **1st stage of the energy transition**, Uruguay is starting to de-fossilise further sectors, such as transport and industry, which are the largest users of fossil fuels today. Uruguay aims to make use of the opportunities offered by decarbonisation. This process is subsumed as the **2nd stage of the energy transition**. The key question is which requirements have to be met in order to achieve a sustainable two-phase energy transition, which means avoiding negative EESG effects by coupling these sectors with electricity provided by renewable energy sources.

Pilot project on heavy road transport in Uruguay: Instead of using lithium-ion batteries in buses or trucks, fuel cells are a promising alternative for powering long-distance transport and heavy vehicles. Both technologies have some advantages and disadvantages, thus it is important to establish what is practicable and sustainable under real world conditions or how these conditions could be adjusted. Uruguay is willing to implement a first pilot project to explore the feasibility of a hydrogen-powered heavy transport system. The pilot project shown in figure 3 below is supported by the Uruguayan government. It is one of the options that the Uruguayan government can support within the framework of the call which, at the time of publishing this paper, is underway within the framework of the National Research Agency and Innovation (ANII[9]).

TABLE 2: Renewable Energy Sources in Uruguay

Source: ADME (2022), own illustration

[GWh]	2020	2021
Wind	5,456	4,971
Solar	423	436
Biomass	1,027	1,032
Hydropower	3951	5,159*
Thermal power	805	2451
Import	514	55
Export	1,148	2,820
Domestic use	11,029	11,285

* Exports account for the largest share of fossil fuels (mainly to Brazil), as is reported in the BEN 2021.

8 IRENA (2021): Executive Summary: Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020_Summary.pdf?la=en&hash=A27B0D0EF33A68679066E30E507DEA0FD99D9D48 retrieved on 19.05.2022 17:00

9 ANII is the Spanish acronym.

ANII, the Ministry of Industry, Energy and Mining (MIEM) and the Uruguayan Technological Laboratory (LATU) have created the Green Hydrogen Sectoral Fund, with the aim of financing research, innovation and training projects in this area. Through this call, funding and support are provided for the construction, production and use of green hydrogen and its derivatives. Among its uses are heavy-duty transport or buses, e-methanol, e-kerosene, green fertilisers and blending with natural gas. The call is open to different possibilities in terms of renewable energy source, scale and location[10].

Further reading: The Agora study (2018) presents the differences between the various propulsion systems, engines with fuel cells and internal combustion of PtL as well as electrical ones.[11]

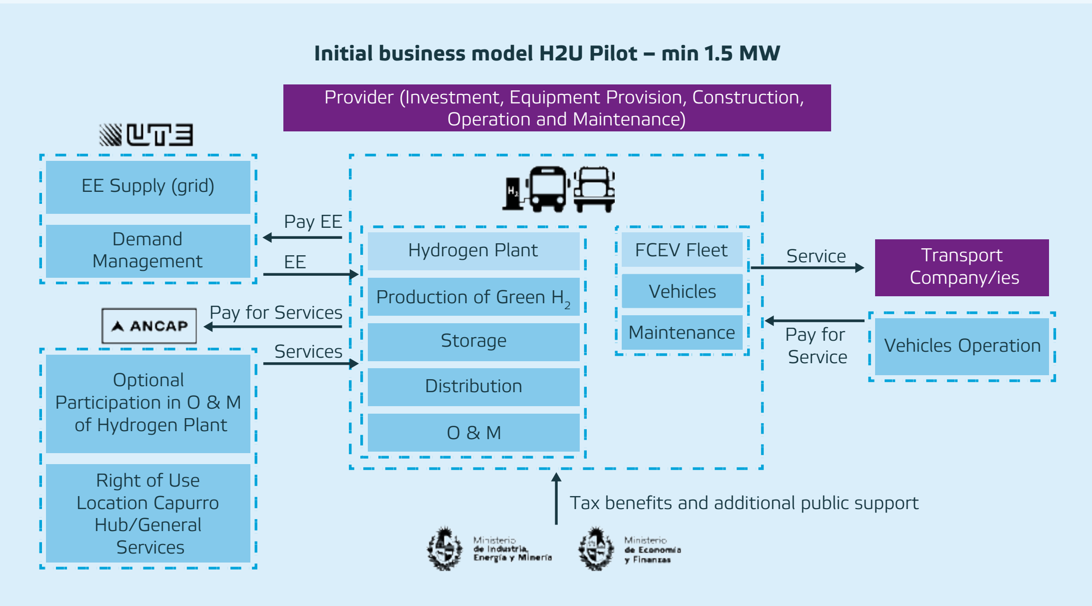


FIGURE 3:
Pilot project to power buses and heavy trucks with green hydrogen in Uruguay

Source: MIEM (2021)

10 For further information, see the following link (in Spanish): https://www.anii.org.uy/apoyos/innovacion/303/call-to-projects-of-green-hydrogen/#:~:text=ANII%2C%20el%20Ministry%20of%20Industry,and%%2020training%C3%B3n%20in%20this%20tem%C3%A1tica

11 Agora (2018) https://www.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf retrieved on 17.04.2022 09:20

Introduction: Hydrogen Economy

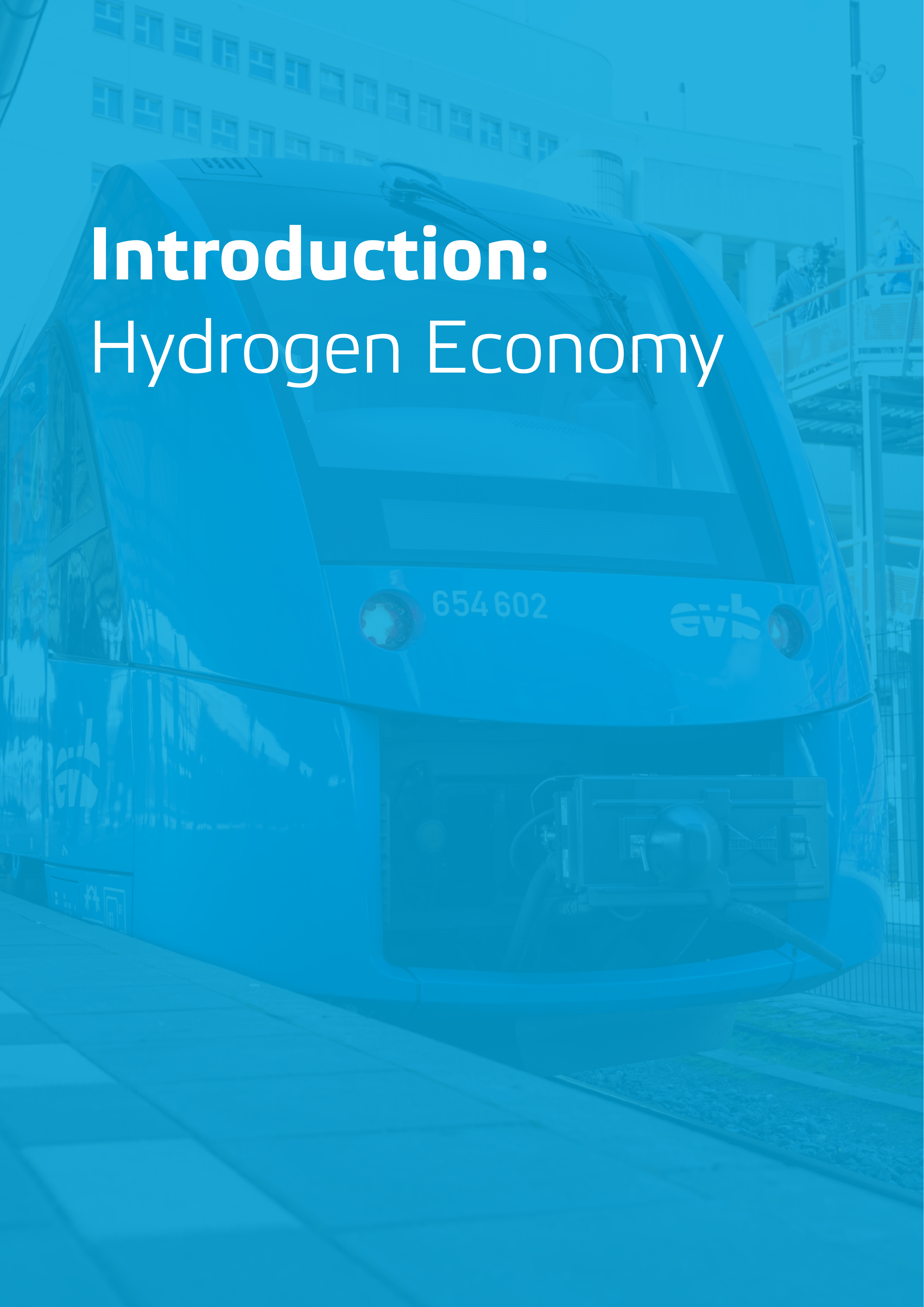


FIGURE 4: Industrial sectors worldwide depend heavily on fossil fuels to operate

Source: IEA (2020), Dena (2019), PtX-Hub (2021)

Current opinion regards hydrogen as an element with vast potential for fostering a more sustainable energy vector and as input to greening many industrial production processes. An important part of this opinion was triggered by policy developments in the European Union[12] and specifically Germany[13], both striving to ramp up a new **"hydrogen economy"** through financial support for new applied research and technological readiness and as a means to achieve carbon neutrality by mid-century. The realisation of this potential, however, requires the upscaling of available processes and technologies and series manufacturing of components such as electrolyser stacks to achieve an industrial level.

Thus, the hydrogen economy holds **potential for climate and sustainability purposes**. The Sustainable Chemistry community sees the supply of green hydrogen as a long-term project and considers it to be the last mile of de-fossilisation processes for a carbon-neutral and climate-friendly development. In the short to medium term, the priority is to further **expand renewable energies** – also as a prerequisite for producing green hydrogen, promoting energy efficiency and avoiding unnecessary transport, shifting to more environmentally friendly modes of transport and improving transport efficiency. Green hydrogen uses power exclusively from renewable energies and is therefore the only climate-neutral and technically safe option. Technical reformation of processes and economic incentives are required to develop it. In addition, green hydrogen (and its downstream products) should be used as energy carriers primarily in areas where it is not possible to use power directly and therefore more efficiently.

12 COM (2020) https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf retrieved on 17.04.2022 09:25

13 BMWI (2020) https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6 retrieved on 17.04.2022 09:30

In order to achieve complete de-fossilisation, **hydrogen and its downstream products will be required as an energy storage medium** for bulk and non-electrifiable transport by sea, air and road. Likewise, it is used as a building block in the chemical, oil and steel industries, along with, in the case of the chemicals industry, alternative, non-fossil carbon sources. Due to the considerable conversion losses, the synthesis and use of synthetic fuels in cars is five to six times less efficient than batteries and therefore makes little sense[14]. From today's perspective, the use of green hydrogen is particularly attractive in the chemicals industry, where hydrogen – still traditionally derived for the most part from fossil fuels – is used in the production of ammonia and methanol and in hydrogenation reactions, including hydrotreating in refineries. It is also used in oil processing and in steel production, where it substitutes coal. With the help of green hydrogen, companies can make their production processes climate neutral. Raising prices for CO_2 certificates will be a further incentive for companies to continue in this direction.

Due to their limited potential for renewable energies, industrialised and post-industrialised countries will have to cover a large proportion of their hydrogen requirements through imports. Water electrolysis is considered to be the primary technology for future hydrogen production. The difficulty of transporting H_2 necessitates a costly infrastructure. In many cases, therefore, conversion to a more easily transportable PtX product should be considered.

14 Agora (2018), Agora Verkehrswende, Agora Energiewende and Frontier Economics: The Future Cost of Electricity-Based Synthetic Fuels, p. 12, fig. 2, see also PtX-Hub (2021), Training on Green Hydrogen, Uruguay. 27. – 28.10.2021, pp. 17, 165

TABLE 3:
Electrolysis technologies

Source: based on Schmidt et al. (2017) and Weltenergierat (2018), 62

Electrolyser	Alkaline	Polymer Electrolyte Membrane (PEM)	Solid Oxide	Anion Exchange Membrane
Lower dynamic range (%)*	10 – 40%	0 – 10%	> 30%	n. a.
Voltage efficiency	62 – 82%	67 – 82%	< 110%	n. a.
Critical materials	Pt, Co	Pt, Ir, Ru	Gd, Zr, La, Ce, Y	–
TRL	8 – 9 Mature	8 – 9 Commercial	5 – 6 Demonstration	2 – 3 Research

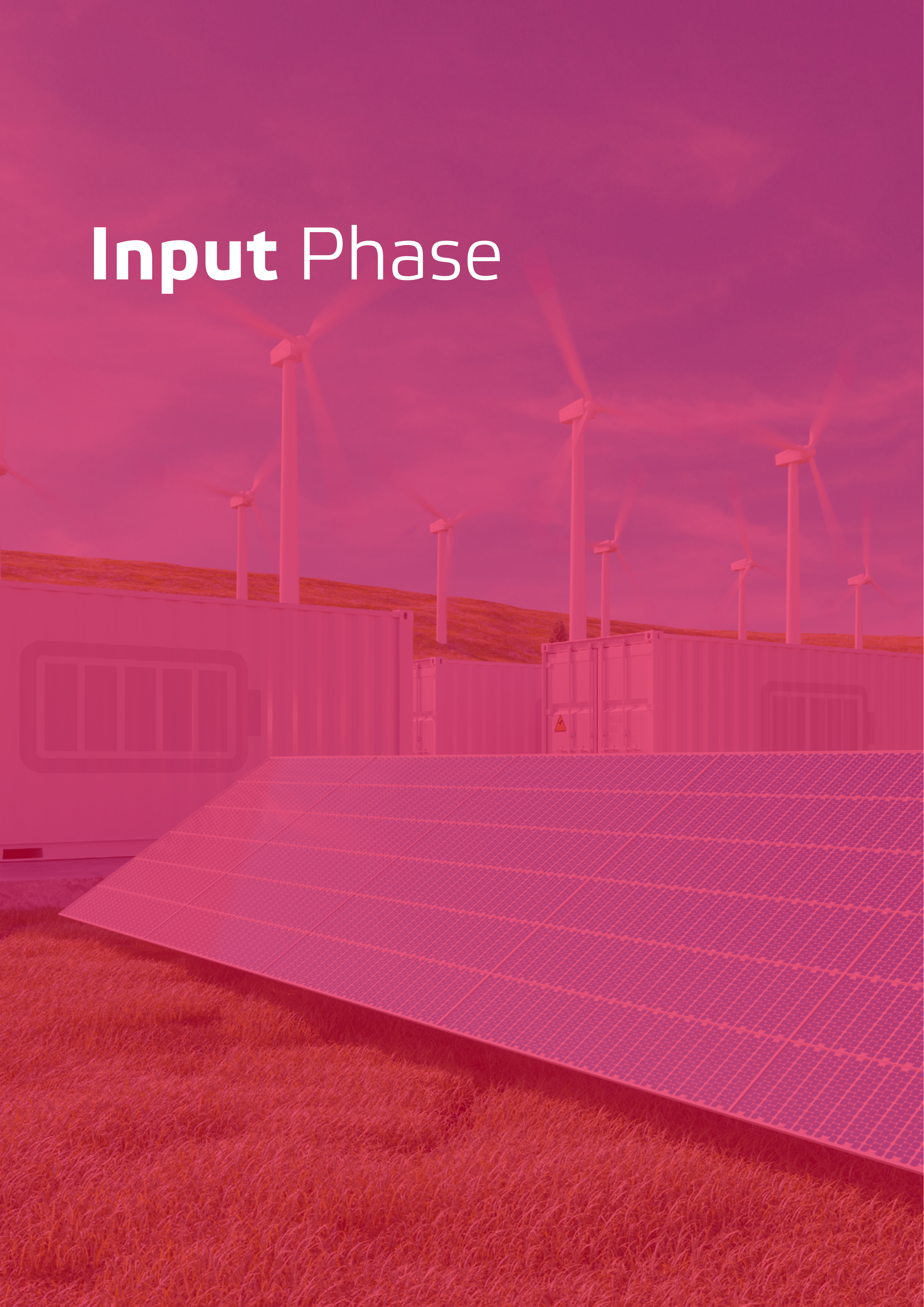
* Minimum operable hydrogen production rate relative to maximum specified production rate

It is essential that the efforts towards **energy security in importing countries considers the interests of exporting countries.** Thus, potential importing countries must ensure the creation of local value chains, equal access to energy and the reduction of domestic CO_2 emissions. Preferrable production sites are situated in countries with high potential for power generation from renewable energies and low power generation costs, and in which political stability and compliance with social and environmental standards are guaranteed.

To ensure truly sustainable production, the entire value chain should be analysed, from the synthesis of green hydrogen to ways to store and transport hydrogen or other PtX products as alternatives.

The prevailing technology is **alkaline electrolysis,** which already today is available on a large scale. In the future, **Polymer Electrolyte Membrane (PEM)** electrolysis can be even more efficient than alkaline electrolysis. However, PEM has the most limitations in terms of materials supply. Several strategies are already part of the research agenda and can help to overcome this barrier. **Solid Oxide** technology is not available at the present time since it is not sufficiently developed. However, it has considerable potential because it can be operated at a higher efficiency rate (see table 3). A combination of waste heat from a chemical process and new technologies such as **Anion Exchange Membrane** electrolysis can bring together the advantages of alkaline electrolysis and PEM electrolysis.

Input Phase



Surplus renewable power not used in the electricity grid by other consumers can be converted into hydrogen by water electrolysis as the primary process. By applying different chemical process steps, the green hydrogen can be used for PtX production.

The PtX process, like any chemical process, can be described by three steps: **input, process and output**; that is, what goes in as educt, how it is processed and what are the end products[15].

In the consultation workshop, ISC_3 took the three steps input, process and output and built a matrix with the EESG factors for each of them. In addition, a SWOT analysis was conducted and **strategies derived for Uruguay** (MIEM). In the virtual workshops, ISC_3 used collaborative tools, such as virtual whiteboards and polls, to identify the sustainability criteria that needed to be considered in order to avoid harmful side effects. The main focus of ISC_3 in the stakeholder dialogue lay on the sustainability aspects of and effects on the EESG criteria[16]. In the workshop, Side Effects of PtX, experts discussed the following questions:

How can we avoid CO_2 emissions as a by-product in chemical processes?

Some **chemical conversions**, e.g. ethylene oxide production, cause process emissions, often called non-energy-related CO_2 emissions.[17] Such emissions are also produced in fermentation processes such as bioethanol production. These emissions are unavoidable, hence they can only be compensated or the products should be based on renewable carbon sources, such as bioethanol.

There is a need to develop new processes and products. Most of the CO_2 output related to chemistry comes from fossil energy. Carbon is a valuable source in organic chemistry; in processes such as cemented steel production it is unavoidable, but it can be reduced, which is why recycling plays an important role.

How can we make CO_2 capture effective for PtX?

In a transition phase, CO_2 from industrial point sources can be captured and valorised (CCU), as these off-gases have relatively high concentrations of CO_2 and can assist decarbonisation in other sectors where CO_2 mitigation is difficult or, as in the case of the cement industry, largely impossible. Apart from such unavoidable emissions, CO_2 should, in the long term, stem from biological sources, e.g. from the production of bioelectricity from solid biomass, the processing of cellulose pulp or from the atmosphere by direct air capture. For the latter, energy consumption has to be considered against the backdrop of the very low CO_2 concentration in ambient air and land use due to capture plant footprints.

How can we desalinate seawater in countries with a lack of freshwater?

Does desalination make sense? This is not relevant for Uruguay today because there are sufficient water resources available, but it is a general topic and, due to climate change, water shortages may occur worldwide. Hydrogen production requires large amounts of freshwater and also generates wastewater, which requires efficient treatment and ideally the valorisation of concentrates rather than disposal.

15 See figure 7: Overview of chemical processes to convert hydrogen and related PtX products

16 Environmental, economic, social and governance-related aspects. Key characteristics for Sustainable Chemistry are described in ISC_3 (2021): https://www.isc3.org/fileadmin/user_upload/Documentations_Report_PDFs/ISC3_Sustainable_Chemistry_key_characteristics_20210113.pdf retrieved on 17.04.2022 10:20

17 See also Annex B.

	E Environmental	S-E Socio-Economic

Input

E – Environmental

- What steps are necessary for Uruguay to achieve more de-carbonisation and de-fossilisation in the energy, chemicals and mobility sectors as well as in agriculture?
- How to manage desalination of seawater in countries with lack of freshwater? Does desalination make sense?
- How to achieve CO_2 neutrality: bioproducts vs. direct air capture (e.g. a certificate)
- How to overcome the space issue (land use) for biofuels etc.
- Market integration: on- and off-grid; grid-connected systems can react to market dynamics and also can increase the profitability of PtX
- For the transition and more/new infrastructure for H_2 and PtX much more cement and steel are needed. How to manage their production in sustainable way, considering those industries as the most unsustainable in terms of energy, pollution or difficult, expensive or non-existing recycling etc.?
- Low carbon = high metal & high energy demand
  - **Energy demand:** green H_2 raises energy demand (in comp. to fossil)
  - **Metal demand:** rare & precious metals + common metals
  - **Water demand:** 9 t water for 1 t H_2
- Radioactive waste as by-product of rare metal mining
- Space for hydroenergy
- CO_2 emissions as by-product in chem. process
- CO_2 capture for PtX (DAC? insufficient)
- Reduction of platinum group metals
- High potential for RE in UY

S-E – Socio-Economic

- How to overcome the lack of general knowledge and acceptance of H_2?
- Need of local value chain creation for new jobs via innovation
- Dependence on electricity prices (70 – 75% of levelised costs of H_2 are electricity costs)

Process

E – Environmental

- How to overcome the scarcity of rare metals? (substitution of metals, using new metals or technologies)
- Where do rare metals come from and where are they used? (e.g. iridium for alkaline electrolysis)
- How to push transition from single-use products to the real circular economy
- How to overcome the scarcity of rare metals considering that there will be not enough of them in the future to cover the massive industrial production of H_2?
- What alternatives for rare and precious metals are there?
- Alternative PEM membranes (fluorine!)
- Further research on catalysts with non-scarce metals as alternatives
- Recycling of electrolyser components or recovery of used rare metals
- Seawater desalination needed in some parts of the Earth to provide freshwater for electrolysis

S-E – Socio-Economic

- How to protect labourers and the negative impact on the environment in the event that mining and producing companies do everything to avoid standards for the sake of profit. (fair trade certifications?)
- **How to lower prices for rare metals or their (very expensive) recycling? (e.g. lithium).**

Output

E – Environmental

- What energy balance do these different outputs have? (PtX product vs. H_2 vs. electricity)
- What is the difference between off-grid and on-grid electricity systems? (e.g. wind farms connected to each other vs. centralised electricity network)
- Is it possible (and how) to use the existing infrastructure (e.g. for natural gas transportation and storage) for H_2?
- What specific issues are connected to different outputs (e.g. ammonia for agriculture = possible over-fertilisation).
- Transportation = environmental risks
- How different are products on the output side in different countries and regions?
- Oxygen as a by-product of electrolysis can be used e.g. in hospitals
- Storage
  - High pressure (350 bar)
  - Cryogenic storage (low temp)
- The energy demand for the storage and transport of green H_2 is higher than that for e.g. grey H_2 (natural gas)
- Material-bound: liquid organic hydrogen carriers (e.g. metal organic frameworks, metal hydrates, etc.)
- PtX-product: Ammonia Methanol
- Over-fertilisation
- Transport of electricity vs. H_2 vs. PtX products (e.g. ammonia)

S-E – Socio-Economic

- **What conditions are to be met to achieve low production prices in the region? (incentives?)**
- **Which off-taker industry should be the first to start using green H_2 and PtX?**
- **What are the constraints for these regional markets?**
- How to have a transition to H_2 and create new jobs?

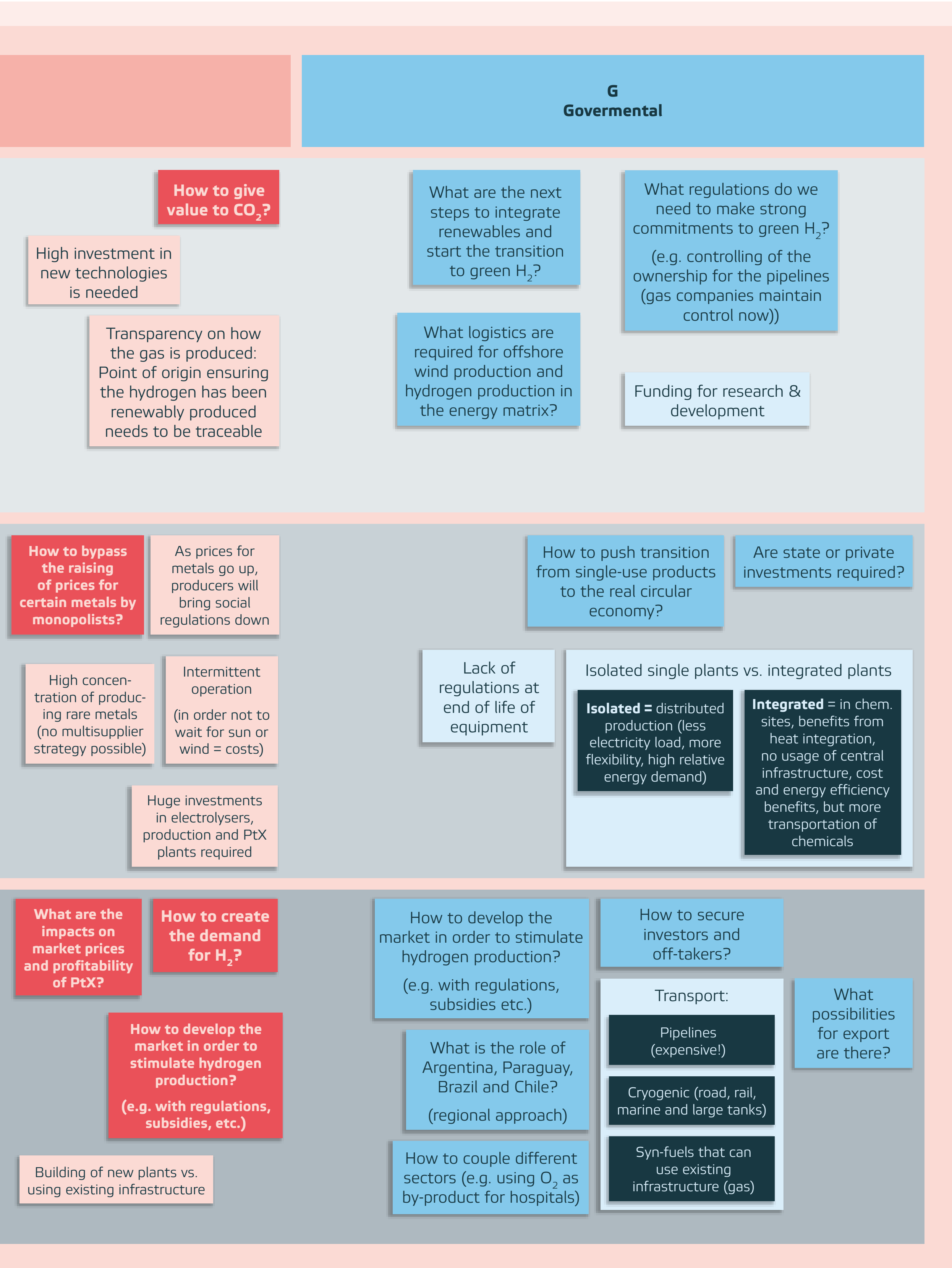


FIGURE 5:
Questions and discussion topics on EESG criteria in the PtX process

Source: ISC_3 (2021b): Workshop Side Effects of PtX on 29.10.2021

a)	Renewable (carbon-neutral) electricity instead of fossil sources as the energy supply both for running utilities such as pumps, compressors, etc. and for the production of green hydrogen itself using electrolysers	Electricity
b)	Sustainable carbon sources (CO_2), for example from biomass, waste plastic after recycling, etc. or from direct air capture	CO_2
c)	Freshwater	Water
d)	Metals, especially precious metals and other critical elements for photovoltaics, wind power plants, electrolysers, catalysts, etc.	Metals

TABLE 4:
The main requirements for carbon-neutral production

Source: Bazzanella (2021), 4 (adapted)

The following four factors are essential for the success of renewable projects: 1. investors willing to take some risk, 2. EPC (skilled engineers), 3. technical solutions that are reliable and cost-effective and 4. favourable conditions, both in terms of climate and regulatory environment.

Further research is needed in order to replace critical metals by more common metals and non-metal materials (e.g. for electrodes). To enable recycling, the complexity of materials must be reduced (e.g. less complex mixtures on atomic level as well as product/item diversity). Ideally, the producer can take the materials back and reuse them. This happens, for example, for ETFE plastic films. This must be documented, and the information must be made available to the user ("product pass", traceability). Valuable materials will otherwise be treated as "normal" waste, which would be problematic. In the example of ETFE films, fluorine or fluorine compounds, which are very toxic, could be released when incinerating them in a normal waste combustion plant.

In addition, a **co-electrolysis** of water and CO_2 reduces CO_2 to carbon monoxide (CO). Starting with synthetic gas, a co-synthesis of hydrogen and carbon monoxide takes place, which yields synthesis gas – this is a starting point of many chemical value chains, e.g. via methanol. By adding further chemical steps, longer-chain hydrocarbons (for example synthetic fuels[18]) can be produced in this way.

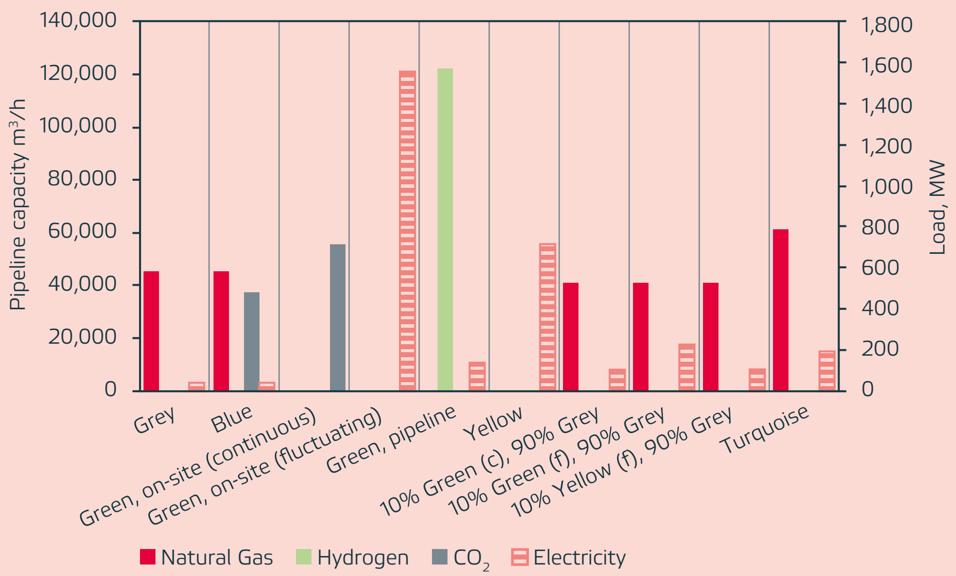


FIGURE 6:
Infrastructure implications – example of different NH_3 plant configurations

Source: Bazzanella (2021), 5

18 Further reading: https://www.kopernikus-projekte.de/en/ retrieved on 17.04.2022 10:40

Challenges in the Input Phase:

For the production of hydrogen, very abundant and additional renewable energy is required. The demand is larger in comparison to conventional processes because chemicals and materials are built up from water and CO_2 as feedstocks, both being very low energy molecules compared to fossil feedstocks that contain high energy. Figure 6 shows that the electricity load of a green hydrogen plant is up to 45 times higher compared to the processing of natural gas.

Major investments in renewable power plants, electrolysers and production of PtX are necessary. Resource demand is high:

- Water: Nine tonnes of water stoichiometrically per one tonne of hydrogen produced[19]
- Metals: Increasing volumes are needed for wiring, piping and general plant construction. Additionally, rare and precious metals are needed as catalysts.
- Steel, aluminium and concrete are needed in large amounts to ramp up the renewable technologies.

Environmental and social issues result from **large infrastructure projects**: Hydropower relies on large dams that require vast amounts of materials (with associated emissions and nature depletion) and energy for their construction and which impact on the landscape. Local inhabitants are often forced from their land, and there is also a negative impact on animals and plants. Groundwater composition is affected; salination of soils often happens in the land beneath. An early example for studying such adverse impacts is the Aswan Dam on the River Nile, with its effects on the environment, soil fertility, cultural heritage, agriculture and water balance. Decreasing rainfall and more heavy, often erratic precipitation events, including increasing sediment load due to climate change, affect some countries, and the huge investments in large hydropower dams are already questioned today. Many small projects and a regionally commensurate, balanced renewable energy mix can reduce such vulnerability, increase resilience and lower the negative impact on the ecosystem.

19 Bazzanella A. (2021): Aspects of Hydrogen and PtX Infrastructure; presentation at the ISC_3 Workshop on 29.10.2021, p. 9

Process Phase

During the ISC_3 workshop, Side Effects of PtX, experts explored and discussed the following questions: How can we overcome rare metal scarcity? Under which conditions do isolated single plants have advantages over integrated ones? Can, in principle, electrolysers and PtX plants be used in smaller production units in remote areas, provided access to water, renewable power and CO_2 is ensured? How can we protect workers and reduce the negative impact on the environment if mining and manufacturing companies do everything to circumvent standards for the sake of profit?

Water electrolysis and PtX technologies based on renewable energy open up **a new production paradigm** for the large-scale manufacturing of hydrogen, synthetic hydrocarbons (e-chemicals and e-fuels) and ammonia. To fulfil the carbon demand, CO_2 conversion (carbon capture and utilisation) is also part of the technology portfolio currently being developed. These technologies can serve different functions:

- De-fossilised production of chemicals,
- chemical energy storage of renewable electricity and
- for a transitional period and for limited applications, the de-fossilised production of fuels. However, storing energy in a laborious and energy-intensive way in fuels just to burn them and re-emit the CO_2 captured before could be questionable.

There is a need to explore where non-metal materials (e.g. electrodes) can be used, which challenges they involve and how to reduce the complexity of materials, e.g. how to create less complex mixtures on atomic level as well as product or item diversity in order to enable better recycling. For documentation purposes, a "product pass" and more traceability are required. In addition, producers should take back the products and/or materials at end of life for recycling.

Water electrolysis or co-electrolysis of water and CO_2 are **scalable by increasing the number** of electrolyser stacks. As such, these plants can also be operated on smaller scales. In addition, with the prerequisite of water availability and an available CO_2 source, these technologies are potentially suitable for remote areas and distributed manufacturing, thereby saving transport. Furthermore, these on-site and on-demand technologies have a lower electricity load and higher flexibility. As a downside, highly integrated processes or process chains, common in the chemicals industry, can be challenging, and overall energy efficiency will decrease due to the lack of heat integration. Both relative energy demand and relative investment costs in the plant and utilities are higher.

Options for better costs and energy efficiency include **integrated plants at chemical parks** and sites with central infrastructure and heat integration. For example, combining an exothermic process with an endothermic process can help to increase total efficiency. For instance, a Fischer-Tropsch technology plant can generate PtX-derived carbohydrates and is an example of such an exothermic process releasing heat. If this heat energy is used to power an endothermic process, the heat energy is not wasted but used to run this further process. For example, water solid oxide electrolysis is a suitable process for consuming the heat released from the Fischer-Tropsch reaction. Combining these two chemical processes will increase overall energy efficiency. The challenges of integrated plants are the limited availability of such sites and greater transport of chemicals, CO_2 and hydrogen.

Different sources for the integration of **CO_2 capture** into existing production are available (see table 5 below). A study by RWTH Aachen University[20] assigns a merit order according to the CO_2 concentration and energy demand for capture. Despite the lower concentration of CO_2 in the atmosphere, DAC, compared to the other sources, can be acknowledged as feasible in the future depending on the (un)availability of today's CO_2 point sources and changing conditions for the decarbonisation of the power sector.

Integrated water management can most likely be implemented in integrated plants or central chemical parks using rainwater, rivers, lakes, groundwater, desalination of seawater and future fuel cell operation. Water is used for electrolysers, industrial production, e.g. paper mills, as a chemical input material and in power plants for steam generation as well as cooling water. Water-saving measures are wastewater treatment, zero liquid discharge and limitation of evaporation.

A transition of the global chemicals industry to a green hydrogen economy would result in a **very high energy demand** compared to today – up to 160,000 TWh by

20 Assen, N. V.; Müller, L. J.; Steingrube, A.; Voll, P.; Bardow, A. (2016): Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves. In Environmental Science & Technology, Volume: 50, Issue: 3, Page(s)/Article No: 1093-11012016, 50, 3, 1093 – 1101; Publication Date: January 11, 2016; https://doi.org/10.1021/acs.est.5b03474

High CO_2 concentration = low energy required	Medium CO_2 concentration = medium energy required	Low CO_2 concentration = high energy required
Conventional ammonia Ethylene oxide Hydrogen (SMR) Biogas fermentation Ethanol	Paper mills Power plants Iron & steel plants Cement production	Direct Air Capture (DAC)

TABLE 5:
Sources of CO_2 capture

Source: Assen (2016)

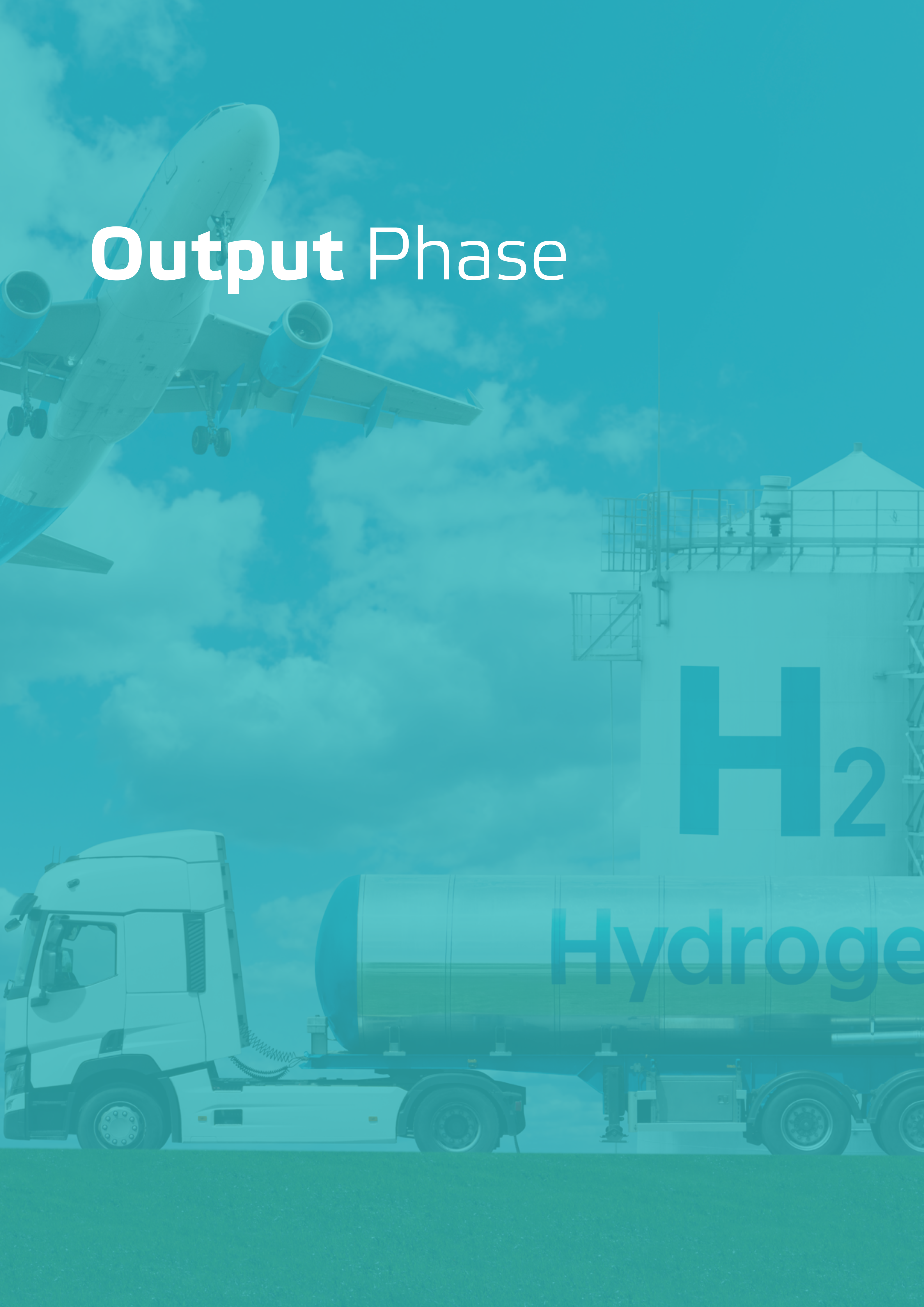
2050[21] – and for a lot of other materials, e.g. rare **metals** and energy-intensive processes. This starts already with the processing of rare and precious metals and minerals: limited availability and accessibility due to geology, technology or politics; complex mining, grinding and extraction. The processes along the value chain generate further waste as well as needing additional chemicals and a lot of energy. For example, silicone and the rare metals cadmium, tellurium or indium are required for solar panels. More materials are necessary for wind power plants: steel, plastics, geotextiles and neodymium. The main research question therefore revolves around the recovery, reuse and recycling of waste materials. Recycling of bulk metals such as steel and aluminium needs a lot of energy and technology as well and requires a well-organised collection and separation system.

Further key questions around the production of chemicals and fuels are:

- Which infrastructure(s) need to be in place for green hydrogen and PtX deployment?
- Where are sites that meet the requirements and offer promising business opportunities?
- Which framework conditions need to be in place to incentivise investments in these technologies?
- Which innovators exist or are emerging?
- Are there industrial symbiosis opportunities through waste gas valorisation without lock-in effects?
- How can we push the transition from single-use products to the circular economy?
- How can we manage the recycling of electrolyser components and the recovery of used rare metals?
- What alternatives for rare and precious metals are there?

21 For green hydrogen plant capacity: 500 kt/a NH3 = 57 t/h = 1370 t/d, H_2 demand: 88 kt/a H_2 = 10 t/h. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e. V. (2022): Perspective Europe 2030 Technology options for CO_2 emission reduction of hydrogen feedstock in ammonia production, January 2022, pp. 30. https://dechema.de/dechema_media/Downloads/Positionspapiere/Studie+Ammoniak.pdf retrieved on 12.04.2022 17:30

Output Phase



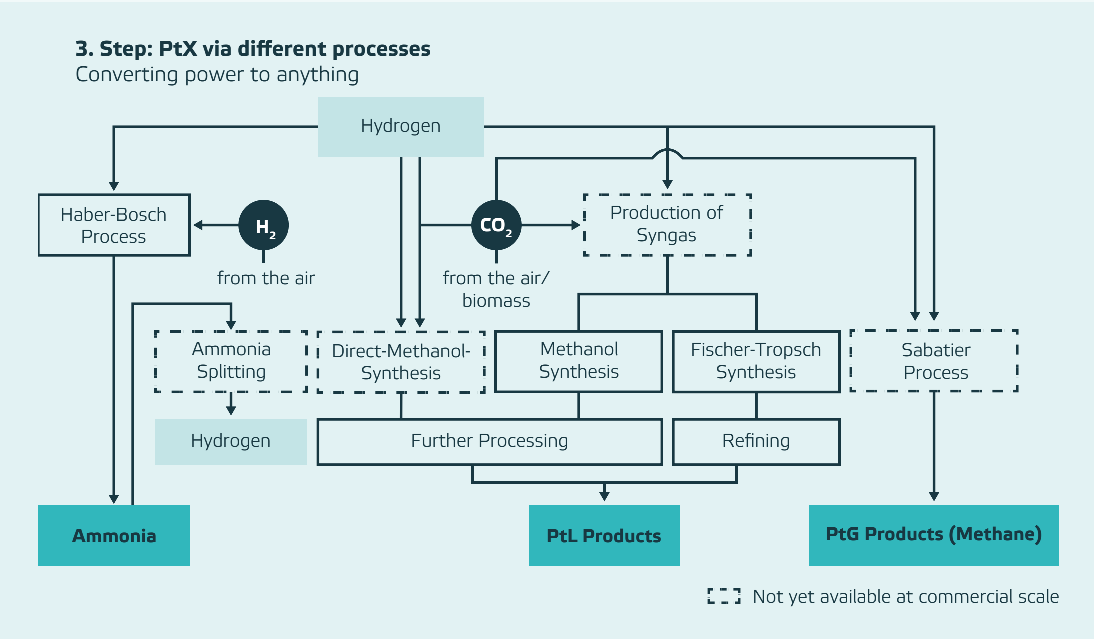


FIGURE 7:
Overview of chemical processes to convert hydrogen and related PtX products

Source: (adapted) SRU, Wasserstoff im Klimaschutz: Klasse statt Masse, 2021, p. 23/fig. 5.

The participants of the working group in the workshop Side Effects of PtX discussed the following questions: How can we promote the transition to hydrogen? Which off-taker industry should be the first to start using green H_2 and PtX?

Fluctuating electricity generation through wind and solar power leads to intermittent operation of electrolysers without power storage. This is challenging for many reasons: first, for system stability and robustness of electrolysers and electrocatalysts; second, the economic viability of the operating mode that has low utilisation efficiency, leading to high relative costs. Using e-fuels for power production, i.e. re-conversion into electricity, does not make much sense, as the overall efficiency of this process chain is low.

Hydrogen can be stored as it is or else bound to a carrier or in a PtX product. **Storage** at a minimum of 350 bar or at temperatures below -253°C requires vast amounts of energy: For example, the energy required for compression to 700 bar is approx. 12% of the energy content of the hydrogen[22]. Novel solutions such as Liquid Organic Hydrogen Carriers (LOHC), metal organic frameworks (MOFs) or metal hydrates are under development. Transfer to a PtX product depends on the industry available, transport strategies and target requirements. The main products are methanol, ethylene, propylene, benzene, toluene, xylenes, ammonia and urea.

Ammonia can be an energy carrier and is one of the most important base chemicals in the chemicals industry. Typically, it is produced in what is known as the Haber-Bosch process by adding nitrogen, as can be seen in figure 7 above. Numerous other chemicals are produced from it. For example, it is used to make nitric acid for the production of fertilisers or explosives or to make urea to produce synthetic resins.

Methanol is produced by adding CO_2 either in direct methanol synthesis or in syngas production. Methanol (CH_3OH) can also be used as a fuel or energy carrier. In some countries, e.g. China, methanol plays a substantial role in further processing in existing chemical value chains, for example to produce ethylene and propylene. Methanol is also a starting material in the production of formaldehyde, formic acid and acetic acid.

22 Peter Kurzweil, Otto K. Dietlmeier: Elektrochemische Speicher. 2nd edition. Springer Fachmedien, Wiesbaden 2018, 8.2 Wasserstoffspeicherung.

Transport of hydrogen requires a developed infrastructure: pipelines (cost-efficient for distances 3,500 – 5,000 km in length[23]), road, rail or marine transport for high-pressure or cryogenic tanks. The infrastructure of existing chemical plants, such as pipelines or filling terminals, can be used to transport gaseous (called PtG) or liquid (called PtL) Power-to-X products. A result of the preparatory work undertaken to define its hydrogen strategy is that Uruguay has decided to analyse the logistics infrastructure which the development of different carriers would imply. One option discussed is to build new port capacities for the shipment of ammonia[24]. Ammonia is both caustic and hazardous in its concentrated form, and large quantities should not be processed or shipped close to settlements. As an alternative, offshore production is currently being discussed, which would be loaded onto ships at sea.

Levelised costs for hydrogen depend essentially on the price of electricity (as the cost of electricity accounts for 70 – 75% of the operating costs in water electrolysis[25]). One of the main questions that arises at the beginning of the transition to a hydrogen economy is therefore: Is it necessary to establish a new hydrogen infrastructure or can the existing gas structure be used? In comparison to natural gas, a 2.7 times higher pipeline capacity is needed for hydrogen due to its lower specific energy content related to density, and investments are consequently high[26]. First innovative projects mix hydrogen in existing pipelines with natural gas and extract it via membrane technology at the point of consumption[27]. Such bridging technologies might be important for realising the 2nd stage of the energy transition.

Further questions related to the production of chemicals and fuels[28]:

Governmental:

- How can we develop the market to stimulate H_2 production?
- How can we secure investors and off-takers? Which off-taker industry should be the first to start using green H_2 and PtX?

Socio-economic:

- How can we achieve a transition to H_2 and create new jobs?
- What are the constraints for regional markets?
- Which conditions must be met in order to achieve low production prices in the region?
- What are the impacts on the market prices and profitability of PtX? How can we promote the use of H_2?

—

23 BloombergNEF, Hydrogen Economy Outlook, 2020, p. 5. https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf retrieved on 12.03.2022 15:50

24 Uruguay Natural (2021): Uruguay maps out a route to pioneer "green" hydrogen, April 12, 2021, https://marcapaisuruguay.gub.uy/en/uruguay-maps-out-a-route-to-pioneer-green-hydrogen/ retrieved on 21.04.2022 12:28

25 Bazzanella A. (2021): Aspects of Hydrogen and PtX Infrastructure; presentation at the ISC_3 Workshop on 29.10.2021, p. 7

26 For green hydrogen plant capacity: 500 kt/a NH3 = 57 t/h = 1370 t/d, H_2 demand: 88 kt/a H_2 = 10 t/h. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V (2022): Perspective Europe 2030 Technology options for CO_2 emission reduction of hydrogen feedstock in ammonia production, January 2022, pp. 30. https://dechema.de/dechema_media/Downloads/Positionspapiere/Studie+Ammoniak.pdf retrieved on 12.04.2022 17:30

27 Source: https://energynews.biz/linde-extracts-hydrogen-from-natural-gas-pipelines/

28 The question arose during the discussions at the ISC_3 workshop Side Effects of PtX in Uruguay in October 2021.

Environmental:

- How can we transport and export H_2? What export possibilities are there and what are the related environmental risks?
- What pros and cons do off-grid and on-grid electricity systems have in conjunction with the production of green H_2? Which impacts do they have?
- Which different products on the output side are suitable for which countries and regions? Which possible side effects do they have?

Uruguay has recently developed a **hydrogen strategy**. Because of the advantageous conditions in the country, such as political and economic stability, geographical position and the extraordinarily high percentage of renewables in the electricity sector (approx. 98%)[29], Uruguay plays a pioneering role in the LAC region, in addition to Chile, acting as an example for other states starting the transition to a hydrogen economy. Different options for implementing a PtX roadmap under consideration of sustainability aspects have been explored and will be discussed with policymakers and the management of industrial companies in the next step in order to decide on programmes and initiate first projects to make the second stage of the energy transition a success.

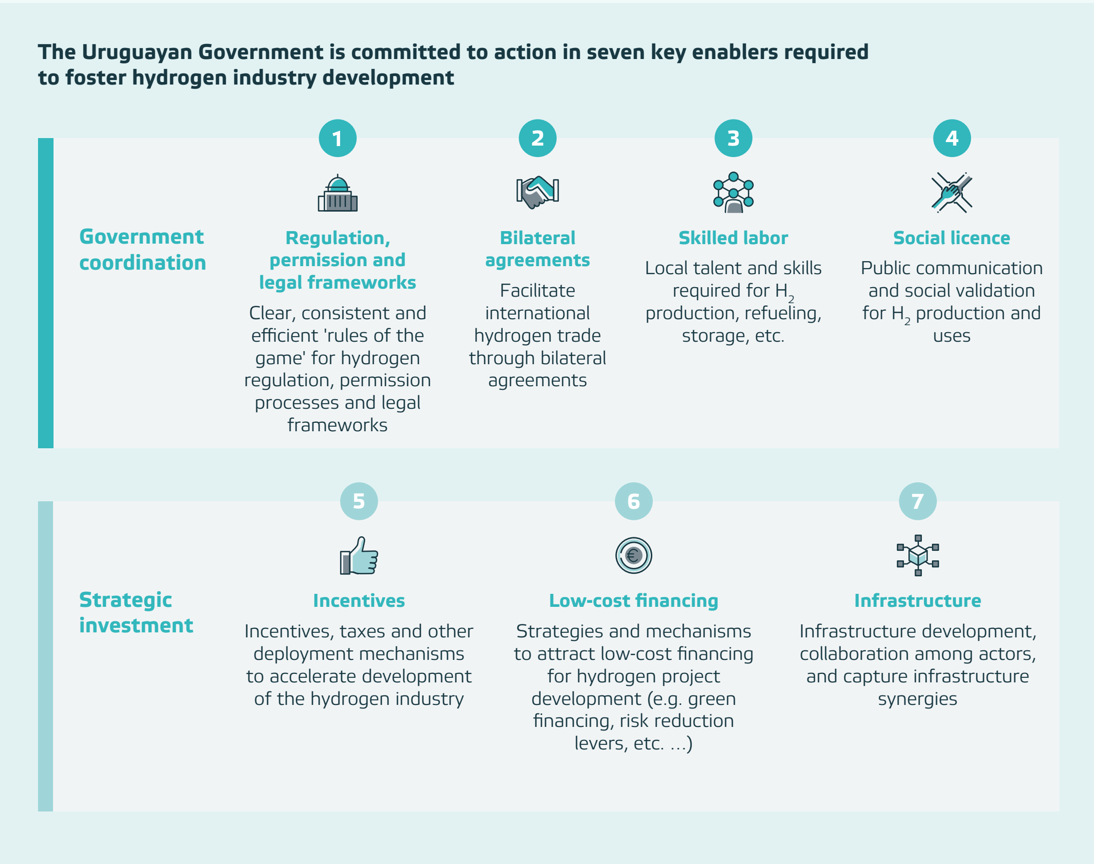


FIGURE 8:
The government's key actions to foster hydrogen in Uruguay

Sources: Gonzalez (2021), 18; McKinsey (2021)

29 Medina, N. (2021): 1st and 2nd Energy Transition in Uruguay, MIEM; presentation at the ISC_3 Workshop on 29.10.2021

De-fossilisation **Strategy**

The **1^{st} stage of the energy transition** means substituting power plants that use fossil fuels and nuclear energy with renewable energy systems in order to meet the country's electrical energy demand. Uruguay is a frontrunner in this regard. The **2^{nd} stage of the energy transition** entails de-fossilising other sectors and applications, such as transport, domestic heating and hot water supply, heat, and chemical feed products in industry, by using green hydrogen and PtX. This is the phase that must be planned and initiated. Uruguay began this phase with the support of the IADB and several technical inputs from McKinsey to create a hydrogen roadmap. In a consultative process, ISC_3 and PtX-Hub assisted MIEM and other stakeholders from Uruguay and Latin America (e.g. ANCAP, UTE, OLADE) with an in-depth analysis of the possible negative social, economic and environmental impacts of this second stage of the energy transition.

ISC_3 Approach

By making use of the experience and credibility of GIZ in the international context and the technical experience of ISC_3 partners, ISC_3 is well-placed to provide support in a developing international hydrogen market and to advise partner countries, public and private clients, and cooperation partners on the associated sustainability considerations. This role is important both in the early phase and when drawing up detailed strategies and standards for sustainable, climate-friendly hydrogen production and use.

ISC_3 asks questions that focus on sustainable chemistry: What do PtX technologies mean for land use? Which resources will become scarce and endanger development in other economic sectors? Can these new technologies compete with further essential social needs and concerns such as food security, the right to affordable drinking water or a just transition to more sustainable energy and mobility systems? Can circular economy approaches provide new ways to offer sustainable solutions to these questions?

Conclusion

Today, the existing chemical system in Uruguay, as in many countries worldwide, is based on petrochemical processes and fossil fuels, i.e. the distillation and cracking of long-chain hydrocarbons. In a green hydrogen vision, the opposite is needed: **the derivation of molecules such as H_2, N_2, CO_2 for direct use or for synthesis into longer-chain molecules for further utilisation in various applications**. This new hydrogen economy, with all the related value chains, requires high levels of capital investment as well as substantial changes to regulatory and framework conditions, among other structural changes. The transformation requires action by many societal groups, such as policymakers, the academic and research communities, and the private sector.

The following list "It is smart…" is not exhaustive but aims to show ways to make these energy transition phases as sustainable as possible. It applies the precautionary principle from the 10 key characteristics of Sustainable Chemistry (see table 1). Ultimately, an inter- and transdisciplinary approach and systems thinking are required rather than case-by-case solutions. The following recommendations are based on the input – process – output sequence and the EESG criteria.

It is smart…

…in renewable energy as an input for green hydrogen production…

- to combine renewable energy sources such as solar, wind, hydropower and (waste) biomass in a way that enables a maximum capacity factor and least cost. Only renewable power sources will lead to green hydrogen.
- to extensively expand renewable energy capacity for PtX production in order to avoid counteracting the phase-out of fossil power plants. This needs to include other sectors such as mobility and industry.
- to consider the stability of the electrical grid and to include storage capacities where necessary.

…in the production of hydrogen and PtX products…

- to identify opportune locations with chemical production sites, possibly enhancing locational advantages for the chemicals industry. Uruguay could extend the supply chain, adding value to hydrogen-based products.
- to identify the industries that use H_2 today and which of them should be substituted by green H_2 first.
- to recycle electrolysers and components, stacks or stack elements; metallurgical recovery of precious metals.
- to reduce the platinum group metals and to use alternative PEM membranes (to eliminate fluorine).
- to use available, stationary (easily accessible and exploitable) CO_2 sources that will still exist in the next decades.
- to avoid idling, e.g. if there is no wind or sun. Continuous rather than intermittent H_2 production is preferable.

…in infrastructure for production, storage and transport…

- to use existing infrastructure, such as pipelines, ports, high-voltage power lines, etc.
- to question transport efficiency: transport electricity versus hydrogen and/or CO_2 versus PtX products.
- to combine and integrate exo- and endothermal chemical processes to improve overall efficiency.
- to run production plants in hybrid operation mode for the transition phase where applicable.
- to avoid investments in greenfield plants – it is better to retrofit existing brownfield plants if possible.
- to also use the oxygen from electrolysis (e.g. for hospitals, bleaching or chemical processes).

…in sector-specific overviews and market knowledge demand markets for hydrogen and PtX…

- to determine the most attractive sector to start with replacing fossil fuels: transport, steel, chemical feedstock, industrial heat, space and water heating. Uruguay has identified heavy transport for a pilot project.
- to improve the efficiency of a PtX product depending on existing infrastructure: ammonia, methanol, Fisher-Tropsch naphtha/fuels. This depends on which drop-in products can be used in existing production assets.

...in environment and climate-related sustainability dimensions...

- to design renewable power plants, electrolysers, fuel cells and other processes for easy dismantling of the individual parts and to return them to the material cycle after end of life.

- to conduct research on the reduction of Pt group metals, alternative PEM membranes, etc. and concepts for the recycling of electrolysers (stack elements, recovery of precious metals, etc.).

- to avoid toxic or environmentally harmful products or substitute these by less critical ones. Transport risks for hydrogen, ammonia, etc. need to be considered.

- to implement necessary resource and waste management.

...in socio-economic and governance-related sustainability issues...

- to consider social impacts that might occur, such as rise in national energy prices, land use, soil salination. Countermeasures should be planned, implemented and their effectivity tracked.

- to take care at an early stage that there are enough qualified professionals and teachers in the industry and in the research sector and to avoid hiring only people from abroad.

- to take rebound effects into account, i.e. decrease in expected gains from innovative technologies that increase efficiency of resource use because of behavioural or other systemic responses.

... in support policies and regulations...

- to consider CO_2 emission certificates in business models.

- to allow all stakeholders to participate and benefit from the transition to a green hydrogen economy.

- to avoid trade barriers or inequities in order to support domestic industry in international competition in its efforts to become more sustainable (example: EU Carbon Border Adjustment Mechanism).

- to collaborate with neighbouring countries in energy trade, research and complementary production.

Outlook

Can these **findings be transferred to every region in the world? Clearly not!** The situation in the MENA region is different. In order to understand what the common requirements are and where decisions must be taken based on regional prerequisites, ISC_3 will look at Morocco in future workshops and has identified a different starting point there: While Uruguay already produces more than 60% of its total energy and approx. 98% of its electrical power from **renewable resources**[30], Morocco relies heavily on oil, coal and natural gas (> 90% of total energy). 90% of electrical energy stems from coal, while the capacity of renewables has barely increased to 20% in the last five years. While the initial conditions in Uruguay are fairly good for producing green hydrogen around the clock due to a high proportion of hydropower and biomass (bioelectricity), Morocco relies on the sun to shine and the wind to blow. Hence, the **utilisation rate** of hydrogen production facilities will be lower and therefore less efficient. In the event that Uruguay does not use the hydrogen further to extend the value chain within the country, i.e. process it into higher added value products, it must be transported across long distances to the off-taker. This will primarily take place by sea. For Morocco, its proximity to Europe with its numerous energy-consuming industries is very advantageous. There is already a gas pipeline in place that can also be used to **transport** hydrogen.

These are only three areas that must be taken into account – **further considerations,** such as political stability, education standards, available workforce, infrastructure quality and existing chemicals industry as off-takers, water availability and many more, are necessary.

To lead a region into a sustainable hydrogen future, being prepared to develop a sustainable hydrogen roadmap and to discuss all three dimensions of sustainability among stakeholders are therefore crucial.

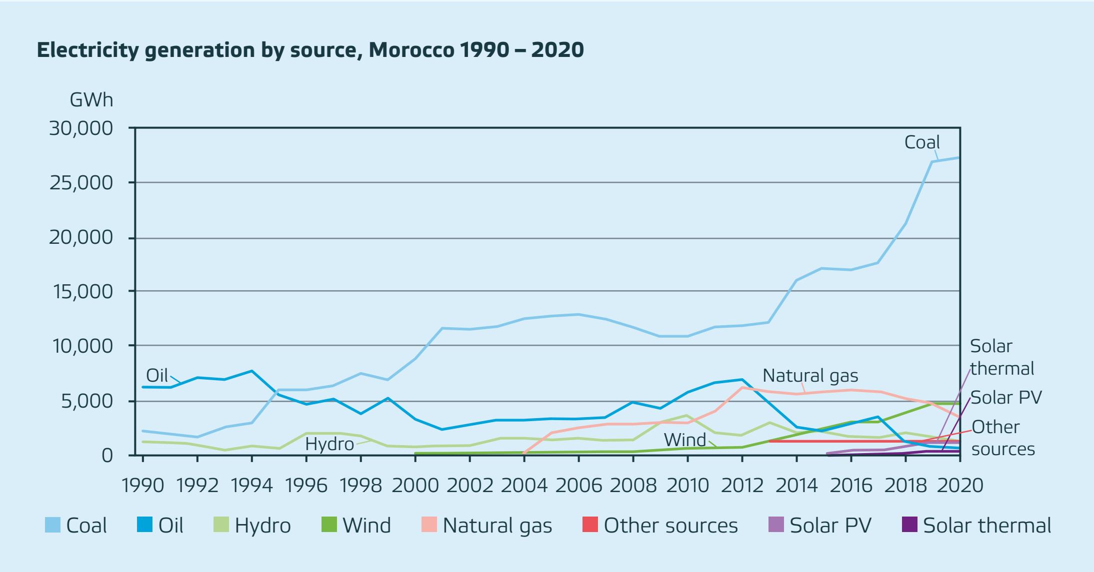


FIGURE 9:
Electricity generation by source, Morocco 1990 – 2020

Source: IEA (2022) https://www.iea.org/countries/morocco

30 Data source Uruguay: https://ben.miem.gub.uy/preliminar.php, retrieved on 07.05.2022 16:15

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Acronyms

ANCAP	Administración Nacional de Combustibles Alcohol y Pórtland (National Administration of Fuels, Alcohols and Portland)
ANII	Agencia Nacional de Investigación e Innovación (National Agency for Research and Innovation)
CO_2	Carbon dioxide
CCU	Carbon Capture and Utilisation
EESG	Economic, Environmental, Social or Governance
EPC	Engineering, Procurement and Construction
ETFE	Ethylene tetrafluoroethylene
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German agency for international cooperation)
IADB	Inter-American Development Bank
ISC_3	International Sustainable Chemistry Collaborative Centre
LAC	Latin America and the Caribbean
MENA	Middle East & North Africa
MIEM	Ministry of Industry, Energy and Mining (MIEM) of Uruguay
OLADE	Organización Latinoamericana de Energía (Latin American Energy Organisation)
PtX	Power-to-X ("X" as an energy carrier made from hydrogen can be gaseous, liquid or solid)
PV	Photovoltaics
SWOT	Strengths, Weaknesses, Opportunities and Threats
URSEA	Unidad Reguladora de Servicios de Energía y Agua (Energy and Water Services Regulatory Unit, Uruguay)
UTE	Administración Nacional de Usinas y Trasmisiones Eléctricas (National Administration of Power Plants and Electrical Transmissions; Uruguay)
TRL	Technology Readiness Level (from TRL 1: Basic principles observed to TRL 9: Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space))

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Annex A: Hydrogen Colours

What is meant by green, blue or grey hydrogen?

Hydrogen is labelled according to the source of the underlying energy carrier used to produce the H_2 and whether carbon capture and storage (CCS) is employed:

Green hydrogen – water electrolysis using electricity from **renewable** energy power plants

Blue hydrogen – fossil fuel source with CCS or electrolysis using non-renewable electricity but at great capital cost for commercially available CCS and H_2 generation equipment

Grey hydrogen – fossil fuel source with no CCS to remove, store and stabilise CO_2

Turquoise hydrogen – methane pyrolysis (thermal splitting of methane) does not produce CO_2 but solid carbon[31]

Further colours of hydrogen production are shown in figure 10.

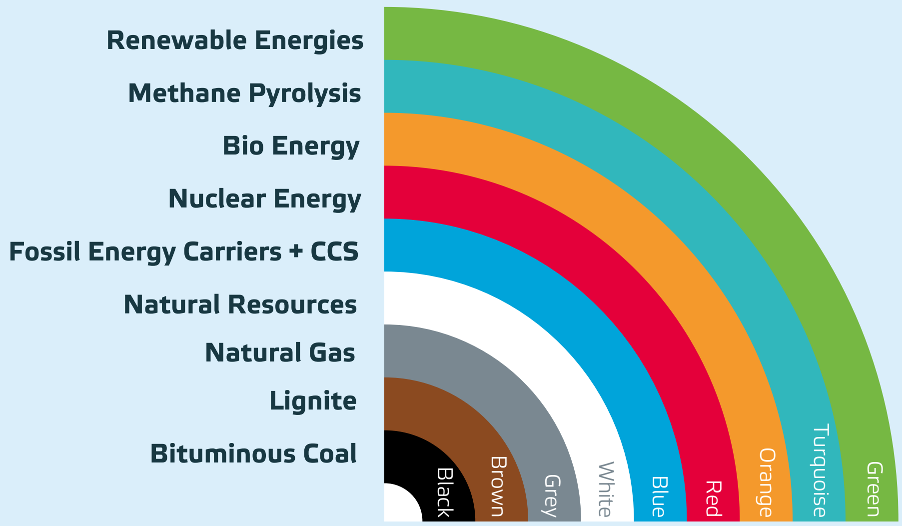

FIGURE 10:
Hydrogen Colours

Source: IKEM (2021)

31 PtX-Hub (2022) https://ptx-hub.org/the-colours-of-hydrogen/

Annex B: Types of Emissions

In chemicals production today, the feedstock used consists mainly of fossil resources. In most cases, they are converted into carbon-containing products. In addition, fossil fuels are also required for running the chemical process to provide heat and electricity.

Two types of emissions stem from this production process:

- Energy-related CO_2 emissions produced through the incineration of fossil fuels — Energy-related
- By-product CO_2 emissions in some chemical processes — By-product

For example, ammonia produced from methane by steam reforming generates CO_2 as a by-product. In order to eliminate the energy-related CO_2 emissions, a replacement of the fossil feedstock with green hydrogen is necessary. However, its production requires electricity, which should come from renewable resources (green hydrogen) in order to build up a carbon-neutral industry. To save process emissions at least partially, processes should be changed or adjusted. An example for a solution is the production of ammonia from hydrogen instead of methane, including nitrogen from the atmosphere, for example, that automatically excludes CO_2 as a by-product.

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